Summary of Technical Results

ONR Grant N00014-82-K-0193

Computer Science Department, University of Rochester

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The results of this grant cover a wide range of issues in knowledge representation, natural language and learning. The early years of the grant primarily center on the development of connectionist approach to representation and language. At the same time, the development of plan-based models of dialog by the PI was setting the ground for a major push in the area of natural language dialog. The principal objective of the dialog project was to develop a system for representing and reasoning about the discourse context in extended man-machine dialogs. The focus areas included the development of a model that captures the structure of natural-language dialog, the development of a general knowledge representation for capturing a wide range of natural language semantics, and the development of a general, error-tolerant parser and semantic interpreter for English that can be guided by discourse information. Specifically, we developed a model of discourse plans that includes actions such as introducing a new topic, as well as the actions of clarifying, correcting or acknowledging parts of the previous dialog. We also explored how the "traditional" language components, i.e. parsing, semantic interpretation and discourse processing, could be adapted to the dialog scenarios.

The best description of the specific results of this project are found in the publications of the groups while under this grant. This report presents these publications together with a brief summary of the importance of each aspect of the project.

1. Connectionist Models

At the beginning of the 80's, almost no work was being pursued in the areas now referred to as connectionist models and neural networks. In fact, little had been done since the early work on Perceptrons, and the negative results of that project were believed to show that the approach was impractical. Jerome Feldman, in the early '80's, disputed this claim and in a series of landmark papers introduced a version of connectionist models and showed that the approach has some significant advantages for certain tasks over conventional approaches. The following papers include some of the early papers that defined and defended the approach and then a significant body of literature exploring connectionist models in various different application areas. Significant results were obtained in the application areas of computer vision, knowledge representation, and natural language parsing.

Cottrell, G.W., "A model of lexical access of ambiguous words," *Proc., Nat'l. Conf. on Artificial Intelligence*, 61-67, Austin, TX, August 1984.

Cottrell, G.W., "Parallelism in inheritance hierarchies with exceptions," *Proc., Workshop on Non-Monotonic Reasoning*, New Paltz, NY, Ocober 1984; *Proc., 9th Int'l. Joint Conf. on Artificial Intelligence*, 194-202, Los Angeles, CA, August 1985.

Cottrell, G.W. and S.L. Small, "A connectionist scheme for modeling word sense disambiguation," *Cognition and Brain Theory 6*, 1, 89-120, 1983.

Cottrell, G.W. and S.L. Small, "Viewing parsing as word sense discrimination: A connectionist approach," in G. Guida and B. Bara (Eds.). *Natural Language Processing*. North Holland, 1984.

Fanty, M, "A connectionist simulator for the Butterfly," TR 164, Computer Science Dept., U. Rochester, January 1986.

Fanty, M.A., "Context-free parsing with connectionist networks," *Proc., Neural Networks for Computing Conf.*, Snowbird, UT, April 1986.

Feldman, J.A., "Dynamic connections in neural networks," *Biological Cybernetics 46*, 27-39, 1982.

Feldman, J.A., "Brains and robots, two weak attempts at the grand synthesis," review, *Cognition and Brain Theory*, 1984.

Feldman, J.A., "Review of *The Architecture of Cognition* by John R. Anderson," *Cognitive and Brain Theory*, 1984.

Feldman, J.A., "Massive parallelism in natural and artificial intelligence," *BYTE*, April 1985.

Feldman, J.A., "Four frames suffice: A provisional model of vision and space," *Behavioral and Brain Sciences 8*, 265-289, June 1985.

Feldman, J.A., "Energy and the behavior of connectionist models," TR 155, Computer Science Dept., U. Rochester, November 1985.

Feldman, J.A., "Connectionist models and parallelism in high level vision," *CVGIP 31* (Special Issue on Human and Machine Vision), 178-200, 1985.

Feldman, J.A., "Connectionist representation of concepts," in D. Waltz and J.A. Feldman (Eds.). *Connectionist Models and their Applications*. Norwood, NJ: Ablex Publishing Company, 1987. Also in *Proc., Conf. on Connectionism in Perspective*, U. Zurich, Switzerland, October 1988.

Feldman, J.A., "Energy methods in connectionist modelling," in P.A. Devijver and J. Kittler (Eds.). *Pattern Recognition, Theory and Applications*. NATO ASI Series in Computer Science, Vol. F30. Berlin: Springer Verlag, 1987.

Feldman, J.A., "A functional model of vision and space," in M. Arbib and A. Hanson (Eds.). *Vision, Brain and Cooperative Computation*. Cambridge, MA: MIT Press/Bradford Books, 1987.

Feldman, J.A., "Time, space and form in vision," TR 244, Computer Science Dept., U. Rochester, November 1988.

Feldman, J.A., "Structured neural networks in nature and in computer science," in R. Eckmiller and C. von der Malsburg (Eds.). *Neural Computers*. NATO ASI Series, Series F: Computer and Systems Sciences Vol. 41 (*Proc., NATO Advanced Research Workshop on Neural Computers*, Neuss, Germany, 1987). Berlin: Springer Verlag, 1988.

Feldman, J.A., "Neural representation of conceptual knowledge," TR 189, Computer Science Dept., U. Rochester, June 1986; in L. Nadel, L.A. Cooper, P. Culicover, and R. Michael Harnish (Eds.). *Neural Connections and Mental Computation*. Cambridge, MA: Bradford Books/MIT

Press, 1989. Also in N. Sharkey (Ed.). *Models of Cognition*. Norwood, NJ: Ablex Publishing Corp., 1989.

Feldman, J.A. and D.H. Ballard, "Computing with connections," to appear in A. Rosenfeld and J. Beck. *Human and Machine Vision*. Academic Press, 1983.

Feldman, J.A. and D.H. Ballard, "Connectionist models and their properties," *Cognitive Science 6*, 205-254, 1982; also in D. Waltz and J.A. Feldman (Eds.). *Connectionist Models and their Applications*. Norwood, NJ: Ablex Publishing Company, 13-62, 1988.

Feldman, J.A., M.A. Fanty, N. Goddard, and K.J. Lynne, "Computing with structured connectionist networks," TR 213, Computer Science Dept., U. Rochester, April 1987; invited paper, *Commun. of the ACM 31*, 2, 170-187, February 1988.

Feldman, J.A., M.A. Fanty, and N. Goddard, "Computing with structured neural networks," *IEEE Computer 21*, 3, 91-103, 1988.

Feldman, J.A. and L. Shastri, "Evidential reasoning in semantic networks," *Proc., 9th Int'l. Joint Conf. on Artificial Intelligence*, 465-474, Los Angeles, CA, August 1985.

Feldman, J.A. and L. Shastri, "Neural nets, routines and semantic networks," *Directions in Cognitive Science*, 1986.

Goddard, N.H., "Representation and recognition of biological motion," *Proc., Cognitive Science Conf.*, August 1988.

Goddard, N.H., "The interpretation of visual motion: Recognizing moving light displays," *IEEE Workshop on Visual Motion*, Irvine, CA, April 1989.

Hollbach (Weber), S.C., "Direct inferences in a connectionist knowledge structure," in TR 209 (*Proc., 1988 Open House*), Computer Science Dept., U. Rochester, May 1988; *Proc., 10th Annual Meeting, Cognitive Science Society*, 608-614, Montreal, Canada, August 1988.

Porat, S., "Stability and looping in connectionist models with asymmetric weights," TR 210, Computer Science Dept., U. Rochester, March 1987.

Porat, S., "Infinite behavior in connectionist models with asymmetric weights," *1987-88 Computer Science and Engineering Research Review*, Computer Science Dept., U. Rochester, October 1987; revised version in R. Trappl (Ed.). *Cybernetics and Systems '88* (*Proc., 9th European Meeting on Cybernetics and Systems Research*). Dordrecht: Kluwer Academic Publishers, 1023-1030, 1988.

Porat, S. and J.A. Feldman, "Learning automata from ordered examples," TR 241, Computer Science Dept., U. Rochester, April 1988.

Shastri, L., "Evidential reasoning in semantic networks: a formal theory and its parallel implementation," Ph.D. Thesis and TR 166, Computer Science Dept., U. Rochester, September 1985.

Shastri, L. and J.A. Feldman, "Evidential reasoning in semantic networks: A formal theory," *Proc., 9th Int'l. Joint Conf. on Artificial Intelligence*, 465-474, August 1985.

Shastri, L. and J.A. Feldman, "Neural nets, routines and semantic networks," in N. Sharkey (Ed.). *Advances in Cognitive Science*. Ellis Horwood Publishers, 1986.

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2. Plan-based Models of Dialog

Since being introduced by Allen, Cohen and Perrault in the early 80's, plan-based models of speech acts have had a strong impact on all work in natural language dialog systems. Throughout this grant period, this approach was extended in significant ways to handle extended dialogs in addition to individual speech acts. In particular, Allen and Litman introduced the method of multi-level plan recognition, where plans were used to represent both the domain information and the discourse structure, and showed how this model could handle clarification subdialogs. The multi-level plan-based representations are now used in most natural language dialog systems in the research community, and are starting to be explored for dialog management in applied dialog systems.

While the plan-based model of speech acts is very attractive from a theoretical standpoint and has wide coverage of the behavior observed, it has proved to be inefficient for use in practical systems. Allen and Hinkelman developed a method that allows the use of a simple structural approach for most speech acts without sacrificing the generality of the method. This technique is now being used in several dialog projects under development.

Allen, J.F., "ARGOT: A system overview," *Int'l. J. of Computers and Mathematics 9* (Special Issue on Computational Linguistics), 1, 1983.

Allen, J.F., "Recognizing intentions from natural language utterances," in M. Brady (Ed.). *Computational Models of Discourse*. MIT Press, 1983.

Allen, J.F., "Discourse structure in the TRAINS project," *Proc., DARPA Speech and Natural Language Workshop*, Pacific Grove, CA, February 1991.

Allen, J.F., "The TRAINS project," *Proc., 4th DARPA Workshop on Speech and Natural Language*, Morgan Kaufmann Publishers, February 1991.

Allen, J.F., S. Guez. L.J. Hoebel, E.A. Hinkelman, K.J. Jackson, A.I. Kyburg, and D.R. Traum, "The discourse system project," TR 317, Computer Science Dept., U. Rochester, November 1989.

Allen, J.F. and E.A. Hinkelman, "Using structural constraints for speech act interpretation," *Proc., DARPA Speech and Natural Language Workshop*, Morgan Kaufmann, Publishers, Fall 1989.

Allen, J.F. and D.J. Litman, "Plans, goals and natural language," *Proc. of the IEEE 74* (Special Issue on Natural Language Processing), 7, July 1986; *1986-87 Computer Science and Engineering Research Review*, Computer Science Dept., U. Rochester, September 1986.

Allen, J.F. and L.K. Schubert, "The TRAINS project," TR 382 and TRAINS TN 91-1, Computer Science Dept., U. Rochester, May 1991.

Hinkelman, E.A., "Relevance: Computation and coherence," commentary, *Behavioral and Brain Sciences 10*, 4, December 1987.

Hinkelmen, E.A., "Plans, speech acts, and conversation implicature," in TR 209 (*Proc., 1988 Open House*), Computer Science Dept., U. Rochester, May 1988.

Hinkelmen, E.A., "Linguistic and pragmatic constraints on utterance interpretation," Ph.D. Thesis and TR 288, Computer Science Dept., U. Rochester, May 1990.

Hinkelman, E.A. and J.F. Allen, "Two constraints on speech act ambiguity," *Proc., Annual Conf., Association for Computational Linguistics*, Vancouver, B.C., June 1989; expanded version appeared as TR 271, Computer Science Dept., U. Rochester, April 1989.

Litman, D.J. and J.F. Allen, "A plan recognition model for subdialogues in conversation," TR 141, Computer Science Dept., U. Rochester, November 1984.

Litman, D.J. and J.F. Allen, "A plan recognition model for clarification subdialogues," *Cognitive Science 11,* 1987.

Litman, D.J. and J.F. Allen, "Discourse processing and commonsense plans," in P.R. Cohen, J. Morgan, and M.E. Pollack (Eds.). *Intentions in Communication.* Cambridge, MA: Bradford Books / MIT Press, 1990.

Martin, N.G., J.F. Allen, and C.M. Brown, "ARMTRAK: A domain for the unified study of natural language, planning, and active vision," TR 324, Computer Science Dept., U. Rochester, January 1990.

Martin, N.G. and B.W. Miller, "The TRAINS-90 simulator," TRAINS TN 91-4, Computer Science Dept., U. Rochester, May 1991.

Traum, D.R., "The discourse reasoner in TRAINS-90," TRAINS TN 91-5, Computer Science Dept., U. Rochester, May 1991.

3. Natural Language Semantics

One of the crucial problems preventing the development of general natural language understanding systems is the lack of a domain-independent model of semantics. Such a model would have to delicately balance the need for an effective reasoning system (and hence an expressively limited logical language), versus the need for simple, compositional semantic interpretation (hence the need for a richly expressive language mirroring the structure of natural language). The problems facing the resolution of this problem are described in detail in Allen (1991) below. Len Schubert has made significant progress on this problem with the development of his episodic logic. While retaining a first-order model theory, he has developed a language that captures many of the structural properties of natural language. As a result, the semantic interpretation process is relatively simple, yet the representation supports effective inference procedures. This work is described in the papers listed below, including the one that won the best paper prize at the first International Conference on Principles of Knowledge Representation and Reasoning in 1989.

Allen, J.F., "Natural language, knowledge representation and logical form," TR 367, Computer Science Dept., U. Rochester, January 1991.

Poesio, M., "Relational semantics and scope ambiguity," in J. Barwise, J.M. Gawron, G. Plotkin, and S. Tutiya (Eds.). *Proc., 1st Conf. on Situation Theory and its Applications* (STASS 90, Loch Crannoch, Scotland). CSLI, September 1990.

Poesio, M., "Dialog-oriented ABoxing," in Z. Ras, M. Zemankova, and M. Emrich (Eds.). *Proc., Int'l. Symp. on Methodologies for Intelligent Systems* (ISMIS 90, Knoxville, TN, October 1990). North-Holland, 277-288, 1990.

Schubert, L.K., "Monotonic solution of the frame problem in the situation calculus: An efficient method for worlds with fully specified actions," TR 306, Computer Science Dept., U. Rochester, August 1989; also in H.E. Kyburg, Jr., R.P. Loui, and G.N. Carlson (Eds.). *Knowledge Representation and Defeasible Reasoning*. Dortrecht: Kluwer Academic Publishers, 23-67, 1990.

Schubert, L.K., "Semantic nets are in the eye of the beholder," TR 346, Computer Science Dept., U. Rochester, May 1990; in J. Sowa (Ed.) *Principles of Semantic Networks: Explorations in the Representation of Knowledge*. San Mateo, CA: Morgan Kaufmann, Publishers, 95-107, 1991.

Schubert, L.K. and C.H. Hwang, "An episodic knowledge representation for narrative texts," *Proc., 1st Int'l. Conf. on Principles of Knowledge Representation and Reasoning*, Toronto, May 1989; TR 345, Computer Science Dept., U. Rochester, May 1990.

Schubert, L.K. and C.H. Hwang, "Picking reference events from tense trees: A formal, implementable theory of English tense-aspect semantics," *Proc., DARPA Speech and Natural Language Workshop*, Hidden Valley, PA, 34-41, June 1990.

Small, S.L., "Parsing as cooperative distributed inference: Understanding through memory interactions," in M. King (Ed.) *Parsing Natural Language*. London: Academic Press, 1983.

Small, S.L., "The story in mind and matter," commentary on article by R. Wilensky, *Behavioral and Brain Sciences*, 1983.

4. Computational Learning Theory

The work in this area concerned the formal underpinnings of language learning. In particular, we have been concerned with developing definitions of language learning that are reasonable for natural language, as opposed to unintuitive artificial languages often used in the literature. This work may lead to hints about useful techniques for learning concrete problems. In addition, the work of Sanjay Jain investigated the effects of faulty data and extra information on the learnability of classes of languages.

Fulk, M.A. and S. Jain, "Learning in the presence of inaccurate information," TR 279, Computer Science Dept., U. Rochester, March 1989.

Fulk, M.A., "Robust separations in inductive inference," presented, *Computational Learning Theory* (COLT 90), Rochester, NY, August 1990; *1990-91 Computer Science and Engineering Research Review*, Computer Science Dept., U. Rochester, 26-30, September 1990; *Proc., 31st Foundations of Computer Science* (FOCS), St. Louis, MO, October 1990.

Fulk, M.A. and S. Jain, "Open problems in *Systems that Learn*," TR 285, Computer Science Dept., U. Rochester, April 1989.

Fulk, M.A. and S. Jain, "Approximate inference and scientific method," TR 313, Computer Science Dept., U. Rochester, October 1989.

5. Representation of Plans and Action

One of the crucial underlying representation problems faced in this project was the representation of actions and plans. The following papers addressed this issue and developed new representations of actions and plans that are more powerful than developed previously, and much better suited to representing communicative plans and speech acts.

Allen, J.F., "Towards a general theory of action and time," *Artificial Intelligence 23*, 2, July 1984.

Martin, N.G. and J.F. Allen, "Abstraction in planning: A probabilistic approach," presented, *Workshop, AAAI Conf. on Artificial Intelligence*, Boston, MA, July 1990.

Martin, N.G. and J.F. Allen, "Combining reactive and strategic planning through decomposition abstraction," *DARPA Workshop on Innovative Approaches to Planning, Scheduling, and Control*, San Diego, CA, November 1990.

Tenenberg, J.D., "Inheritance in automated planning," *Proc., 1st Int'l. Conf. on Principles of Knowledge Representation and Reasoning*, Toronto, May 1989.

Tenenberg, J.D., "The robot designer's dilemma," *1st Int'l. Workshop on Human and Machine Cognition*, Pensacola, FL, May 1989.

Traum, D.R. and J.F. Allen, "Causative forces in multi-agent planning," *Proc., 2nd European Workshop on Modeling Autonomous Agents and Multi-Agent Worlds* (MAAMAW90), 135-139, France, August 1990.

6. Other Research in Knowledge Representation & Models of Parallel Processing

Finally, there are some research results that do not fit well in the above categories but were opportunities created by the work in progress. This includes work in general knowledge representation languages, and work in parallel programming and its application to various AI applications such as natural language, constraint satisfaction, and computer vision.

Allen, J.F. and B.W. Miller, "The Rhetorical knowledge representation system: A user's manual," TR 238, Computer Science Dept., U. Rochester, February 1988.

Chou, P.B. and C.M. Brown, "The theory and practice of Bayesian image labeling," *Int'l. J. Computer Vision 4*, 3, 185-210, June 1990; IBM Research Report RC 15460, T.J. Watson Research Center, February 1990.

Cox, A.L., R.J. Fowler, and J.E. Veenstra, "Interprocessor invocation on a NUMA multiprocessor," TR 356, Computer Science Dept., U. Rochester, October 1990.

Crowl, L.A., "Architectural adaptability in parallel programming," TR 381 and Ph.D. Thesis, Computer Science Dept., U. Rochester, May 1991.

Crowl, L.A. and T.J. LeBlanc, "Architectural adaptability in parallel programming via control abstraction," TR 359, Computer Science Dept., U. Rochester, January 1991.

Gafter, N.M., "Parallel incremental compilation," Ph.D. Thesis and TR 349, Computer Science Dept., U. Rochester, June 1990.

Marsh, B.D., C.M. Brown, T.J. LeBlanc, M.L. Scott, T.G. Becker, P.Ch. Das, J. Karlsson, and C.A. Quiroz, "The Rochester checkers player: Multi-model parallel programming for animate vision," TR 374, Computer Science Dept., U. Rochester, June 1991.

Olson, T.J. and D.J. Coombs, "Real-time vergence control for binocular robots," TR 348, Computer Science Dept., U. Rochester, June 1990; *Proc., DARPA Image Understanding Workshop*, September 1990.

Olson, T.J. and R.D. Potter, "Real-time vergence control," *Proc., IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, San Diego, CA, June 1989; TR 264, Computer Science Dept., U. Rochester, November 1988.

Quiroz González, C.A., "Systematic detection of parallelism in ordinary programs," Ph.D. Thesis and TR 351, Computer Science Dept., U. Rochester, May 1991.

Swain, M.J., "Comments on Samal and Henderson: 'Parallel consistent labeling algorithms'," *Int'l. J. Parallel Programming 17*, 6, December 1988.

Weber, J.C., "A parallel algorithm for statistical belief refinement and its use in causal reasoning," *Proc., Int'l. Joint Conf. on Artificial Intelligence*, Detroit, MI, August 1989.

Yap, S.-K., "PENGUIN: A language for reactive graphical user interfaces," Ph.D. Thesis and TR 344, Computer Science Dept., U. Rochester, April 1990.